W-band Heterodyne Receiver Module with 27 K Noise Temperature

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***Abstract*—We present noise temperature and gain measurements of a W-band heterodyne module populated with MMIC LNAs designed and fabricated using a 35 nm InP HEMT process. The module has a WR-10 waveguide input. GPPO connectors are used for the LO input and the I and Q IF outputs. The module is tested at both ambient (300 K) and cryogenic (25 K) temperatures. At 25 K physical temperature, the module has a noise temperature in the range of 27-45 K over the frequency band of 75-111 GHz. The module gain varies between 15 dB and 27 dB. The band-averaged module noise temperature of 350 K and 33 K were measured over 80-110 GHz for the physical temperature of 300 K and 25 K, respectively. The resulting cooling factor is 10.6.**

***Index Terms*—W-band, heterodyne module, MMIC amplifiers, InP, LNA.**

I. Introduction

The development of scalable, large-format heterodyne focal plane arrays, based on MMIC (Monolithic Microwave Integrated Circuit) amplifiers, offers the potential to revolutionize astronomical spectroscopy, coherent polarimetry and interferometry at millimeter wavelengths and finds applications in broad areas including millimeter-wave imaging, earth sensing, radar and atmospheric sounding. In the past, heterodyne modules with various levels of integration have been reported at W-band [1]–[4].

The continued development of heterodyne millimeter-wave cameras with hundreds of pixels, deployed on large telescopes to rapidly survey large areas of the sky at multiple frequencies and with high spectral resolution will play a key role in future discoveries in radio astronomy. In order to realize these multi-pixel cameras, each pixel must be a complete heterodyne receiver. We demonstrate an ultra low noise, compact W-band heterodyne receiver module using Indium Phosphide (InP) high electron mobility transistor (HEMT) MMIC amplifiers which has been developed as a part of a four-pixel focal plane array. The local oscillator (LO) is set to the center of the band at 100 GHz, and the double sideband (DSB) intermediate frequency (IF) has a bandwidth of 15 GHz, made available in both In-phase (I) and Quadrature (Q) outputs. Sideband separation can be accomplished depending on the application by feeding both IF outputs to a quadrature hybrid.

II. MMIC Module Design and Simulations

Fig. 1 shows a photograph of a single heterodyne receiver module with WR-10 waveguide input on the left and push-on GPPO connectors for the LO input and the IF outputs.

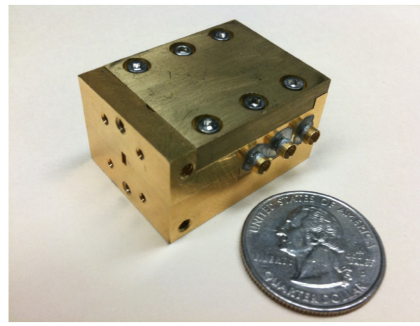

Fig. 1. Photograph of the compact heterodyne MMIC module showing WR-10 waveguide input on the left and push-on GPPO connectors for LO input and IF outputs.

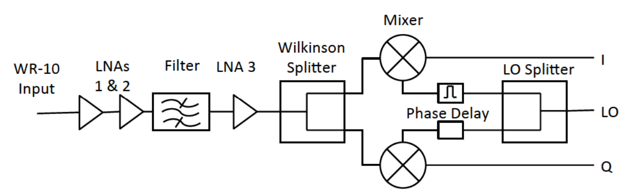

Fig. 2. Block diagram for the heterodyne receiver module.

A. Module Design

As shown in Fig. 2, each MMIC module amplifies the incoming signal using a chain of MMIC HEMT low noise amplifiers (LNAs) and then down-converts the signal to the required IF band. Fig. 3 shows a photograph of a populated module interior with cavity sizes and component placement. The filter between the second and third stages minimizes out-of band power at the third LNA. Attenuators can be included between stages if required. The module lid (not shown), with the pressure ridges around the RF path forms an RF-tight seal. The RF input to the module is WR-10 waveguide which couples the incoming radiation to the LNAs through an E-plane waveguide probe. High-frequency blind-mate push on connectors are used for the LO and IF connections and can plug directly into mating connectors on an IF/LO routing board when used in an array. Biasing of the MMIC devices is accomplished using compact RF-tight feed-through pins in the module.

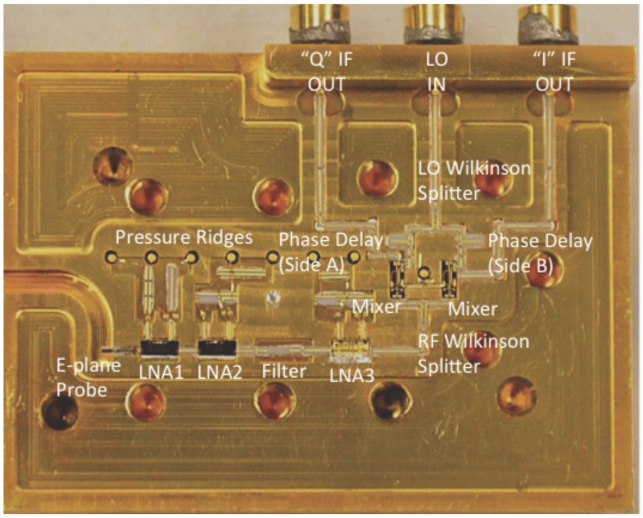

Fig. 3. Photograph showing the interior of a module with cavities and component placements. This module houses three RF amplifiers. However, the results presented here are for a module with the first two MMIC amplifiers only.

The I-Q configuration is implemented for side-band separation using separate second-harmonic mixers for the in-phase and quadrature outputs. As shown in Fig. 2, RF and LO are divided using Wilkinson splitters, and appropriate phase-shifting in LO is achieved using microstrip Schiffman structures made on alumina substrate.

Although the module is designed to accommodate three MMICs, the module presented here has only two MMIC LNAs and does not have any filters. The cavities for the filter and the third LNA are filled with 50 Ω microstrip lines. Third MMIC amplifier can be added later if additional gain is required.

B. Chip selection

The sensitivity of the module is dominated by the performance of the first MMIC LNA. Recent advances in InP transistor technology promise to produce MMIC amplifiers across the millimeter band with noise temperatures only a few times above the fundamental limit imposed by quantum mechanics. The 35 nm gate length InP MMIC LNAs are used here because of their superior noise properties [6].

Chip-to-chip variability poses problems in selection of the MMIC LNAs. Recently, a cryogenic probe station (CPS) has been developed, which allows S-parameter and noise characterization of MMICs non-destructively down to 20 K ambient temperature. Multiple chips were screened using CPS, and the S-parameter data was imported in Agilent's ADS. The input MMIC was a two stage LNA selected based on its noise performance, and the second MMIC was a three stage LNA selected to increase the effective bandwidth of the cascade. Fig. 4 shows the cascaded performance obtained using ADS. The effective bandwidth of the cascade is 31 GHz.

III. Measurement Setup and Performance

Fig. 5 shows the measurement setup used for characterizing the cold noise. The module was mounted inside a Dewar

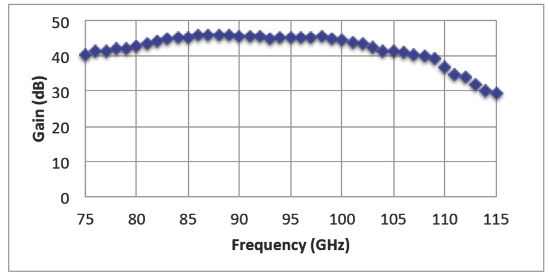

Fig. 4. Simulated performance of the amplifier cascade to achieve maximum effective bandwidth with lowest noise. The calculated effective bandwidth is 31 GHz.

and cooled down to 25 K physical temperature. The noise is measured using the Y-factor method [5] with a variable temperature load (VTL) mounted at the input of the module with a stainless steel (SST) waveguide, thermally isolating the load from the module. The LO is provided using a synthesized signal source and multiplied with a quadrupler in order to produce the required swept signal. The down-converted signal is amplified by a cold IF LNA and a DC-500 MHz room-temperature amplifier. A power sensor with a low pass filter at its input is used to measure the power in the 500 MHz band. As the VTL temperature is varied between 25 K and 50 K, the Y-factor is obtained, and the noise and gain are derived.

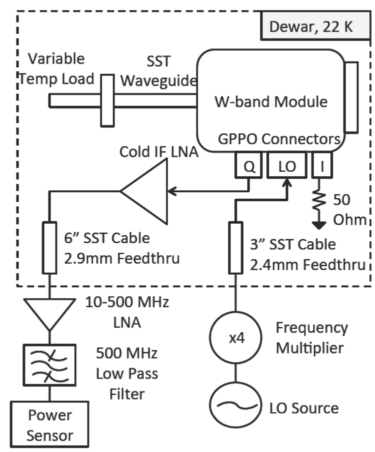

Fig. 5. Measurement setup showing RF, LO, and IF paths.

Spur contamination in the measurement system was characterized separately and is better than 20 dBc from 75 to 111 GHz. For characterization above this frequency, we are implementing a new LO chain with additional filtering.

The output 1 dB compression point for these MMICs is measured to be around -5 dBm. For the cryogenic measurements with the hot load of 50 K, the output power at the second MMIC is approximately -30 dBm. Hence, we are confident that the RF amplifiers are in the linear regime.

Fig. 6 shows the module gain and noise at 300 K from 80 to 110 GHz for both the I and Q outputs. The minimum noise of 310 K is observed at 101 GHz, and the band-averaged noise temperature is 350 K. The drain voltages were set to 600 mV and 1000 mV, and the drain currents were set to 10 mA and 17 mA for the first and second MMICs, respectively.

Fig. 7 shows the module gain and noise at 25 K from 75 to 111 GHz for the I output. A minimum receiver noise temperature of 27 K was achieved, with less than 40 K noise in the range of 75-107 GHz. The band-averaged noise temperature is 33 K. The resulting cooling factor, when comparing room temperature (300 K) noise temperature to cryogenic (25 K) noise temperature is 10.6. The biases for both LNAs were optimized for the module noise temperature, with the minimum achieved at 3 mA drain current per transistor for both MMICs. The drain voltages were set to 600 mV and 800 mV for the first and second MMICs, respectively.

Fig. 8 shows the measured noise as a function of physical temperature. Even at the lowest physical temperature (25 K), the improvement in noise temperature as a result of lower physical temperature is evident. In future tests, we plan to test the module down to 15 K to see if an additional improvement in noise is possible as a result of cooling.

The mixers used in this module are Schottky diode based mixers with a conversion loss of ∼20 dB across the band. This results in the module gain of about 25 dB in the middle of the band. The ripple in the gain is thought to be due to poor matching on the LO port but is still under investigation.

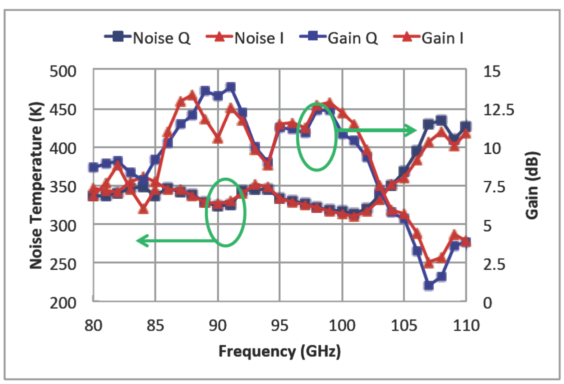

Fig. 6. Measured noise temperature and gain for the module operated at T=300 K. Both I and Q outputs are shown.

IV. Conclusion

A minimum receiver noise temperature of 27 K and a band-averaged noise temperature of 33 K over 75 to 111 GHz were achieved for the W-band heterodyne MMIC module presented here. The module provides both I and Q outputs using two separate mixers. New modules are under development, which will utilize a single resistive HEMT mixer with RF and LO splitting on chip to provide both I and Q outputs. These modules will require considerably lower LO power to make them more suitable for large arrays. Other future improvements may include an IF amplifier and an LO doubler integrated inside the module.

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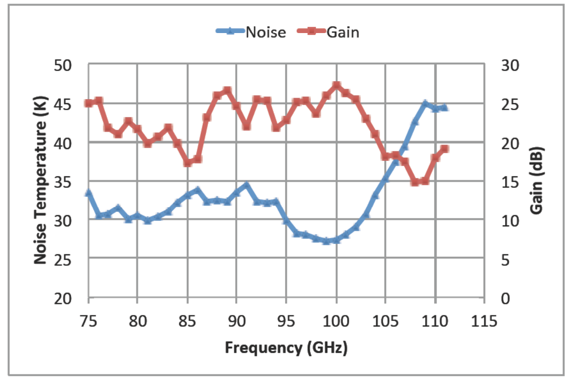

Fig. 7. Measured noise temperature and gain for the module for the I output, when operated at T=25 K. The drain voltages were set to 600 mV and 800 mV, and the drain currents were set to 6 mA and 9 mA for the first and second MMICs, respectively.

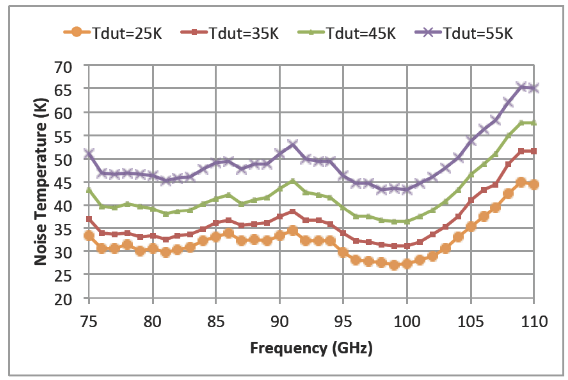

Fig. 8. Measured noise temperature for the module as a function of physical temperature for the I output.

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